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Simulation analysis of models for estimation of empty travel time of vehicles in non-automated material handling systems

In designing or redesigning a facility like manufacturing plant or warehouse, an integral part is a proper selection of material handling system. Despite large alternatives, including automated material handling systems with conveyors or automated guided vehicles, most facilities today use for material handling man-driving vehicles (non-automated discrete material handling system). Proper design of such systems requires determination of required number of vehicles. Determination of empty vehicle travel time is based on either time consuming simulation or non-simulation approach using estimation.
The main goal of this paper is to review and analyse some proposed methods for empty travel time estimation of non-automated discrete material handling systems. Results obtained by estimation methods are compared with the simulation results.

Keywords: *Discrete non-automated material handling system, empty travel time estimation methods, simulation analysis*

1. INTRODUCTION

In designing a new facility like manufacturing plant or warehouse, an integral part is a proper selection of material handling system. Despite large alternatives, including automated material handling systems with conveyors or automated guided vehicles, most facilities use man-driving vehicles (non-automated discrete material handling system), usually forklifts. Proper design of such systems requires determination of required number of vehicles.

Even redesign of existing facilities, like improvement of layout design which is often with the goal of reduction of total transportation, requires analysis of proposed new solution including determination of required number of vehicles. In most existing facilities today, especially smaller ones, we can find only one or few man-driving, non-automated vehicles used for loading, transport and unloading loads between departments and/or machines (workplaces). For determination of required number of vehicles or for calculation of vehicle's utilisation in a proposed redesign, a proper method of calculation of total transport time is required. Based on number of trips between locations (from-to matrix), distances between locations based on layout (distance matrix) and transport/handling parameters (speed of travel, loading times, unloading times), it is quite easy to calculate total time required for loading, unloading and transport of loads. However, determination of empty vehicle travel time is based on either time consuming simulation or non-simulation approach using estimation.

Searching for methods to estimate empty vehicle travel time leads to plenty papers dedicated to automated guided vehicle systems (AGVS), but surprisingly no papers especially dedicated to non-automated transporters. In AGVS there exists a control system with various dispatching rules that are mostly not applicable for transport systems in smaller job shops, workshops or smaller warehouses. Proposed algorithms also usually assume larger fleets where proper scheduling and routing of automated vehicles is required due to the congestions and deadlocks. In smaller facilities only few vehicles are employed, sometimes even only one, with mostly low utilisation.

The main motivation of the research presented in this paper was to review proposed methods for empty travel time estimation developed for AGVS and to analyse their usage for non-automated discrete material handling systems, especially those employing only one or two vehicles. For selected example of production process, varying throughput (production volume) and layout, results obtained by estimation methods are compared with simulation results in order to get insights on estimation errors, possible influence of vehicle's utilisation on estimation error as well as possible influence of layout design (increased full travel time) on total empty travel time and estimation error.

2. EMPTY TRAVEL TIME ESTIMATION METHODS

In this section several most cited methods for empty travel time estimation, analysed in this paper, are shortly presented.

The first analytical models, whose development began in the early 1980's, were designed to provide alternative solution for AGV system design since the

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process of designing a simulation model required much effort and time. Most of the models were logically meaningful and comprehensible, mathematically simple calculation, used to determine the required number of vehicles to carry out transport processes based on pre-known data (transport intensity and distance matrices, and transport and production parameters), in a shorter period of time. Still today analytical estimation methods are preferable than simulation in early stage of design, during selection of material handling systems.

Already in the design of the first models focused on the AGV system design it was noted the importance of determining the time of empty travel, and soon that part of the calculation/estimation became the key item to which the most attention was given. Notation used in models is as follows:

- n number of workplaces
- f_{ij} number of loaded trips (full travels) required from workcenter i to workcenter j
- d_{ij} distance between workplaces, in meters
- D_e total empty travel distance, in meters
- g_{ij} expected number of empty trips from workcenter i to workcenter j
- fd_k number of deliveries to workcenter k
- fs_i number of pick-ups at workcenter i
- d_e average empty vehicle travel distance per trip, in meters

In [1] author presented four models for estimation of number of required vehicles (NRV), however one of them don't estimate empty travel but directly NRV (based on estimated blocking and idle time). Two models were models presented by Beisteiner in [2] – for this paper named BEISTEINER 1 and BEISTEINER 2 model. Fourth model was proposed by author, named EGBELU model.

BEISTEINER 1 model is very simple. It is assumed that the distance travelled by empty vehicles is equal to the distance travelled by full vehicles. Therefore, for a given number of trips between each pair f_{ij} in from-to matrix and distances between workplaces, total empty travel is calculated as

$$D_e = \sum_{i=1}^{n}\sum_{j=1}^{n} f_{ij} \cdot d_{ij} \tag{1}$$

BEISTEINER 2 model is based on calculation of net traffic flows into workplaces, as

$$f_i = \sum_{j=1}^{n} f_{ji} - \sum_{j=1}^{n} f_{ij} \tag{2}$$

If there are more deliveries than pickups at workplace, there will be empty runs form that workplace to some others. And vice versa, if there are more pickups than deliveries at workplace, there will be empty runs to that workplace. Total empty travel distance is approximated as average distance travelled by full vehicles multiplied by number of empty runs between workplaces, as

$$D_e = \left[\frac{\sum_{i=1}^{n}\sum_{j=1}^{n} f_{ij} \cdot d_{ij}}{\sum_{i=1}^{n}\sum_{j=1}^{n} f_{ij}}\right] \cdot \left(\sum_{f_i>0} f_i\right) \tag{3}$$

EGBELU model is based on the fact that in a job shop environment the sequence at which load pickups requests are generated is very random and assumption of fair dispatching rule. It calculates expected number of empty runs between two workplaces i and j from the expected number of deliveries at workplace i and expected number of pick-ups at workplace j using equation

$$g_{ij} = \frac{\left(\sum_{k=1}^{n} f_{ki}\right) \cdot \left(\sum_{k=1}^{n} f_{jk}\right)}{\sum_{i=1}^{n}\sum_{j=1}^{n} f_{ij}} \tag{4}$$

Total empty travel distance is calculated simply multiplying expected number of empty trips between workplaces by distance between them, as

$$D_e = g_{ij} \cdot d_{ij} \tag{5}$$

In [3] authors presented a model for calculation of minimum required vehicles, based on minimization of empty travel. As in BEISTEINER 2 model, this MAXWELL-MUCKSTADT model calculates net traffic flows into workplaces, however determination of empty runs is done by solving transportation problem (minimizing total empty travel). While Egbelu's model is considered as "expected case", this one is considered as "best case". For more details readers are referred to reference [3].

In [4], authors presented a model for empty travel time estimation based on assumption that the vehicles that finish the transportation requirements stay at their current workplace. This assumption assures that the number of empty vehicles leaving a workplace is equal to the number of loads dropped off at that workplace. Similarly, the number of empty vehicles that will be needed at a particular workplace is equal to the number of loads that have to be moved from that workplace. They also assumed that vehicles are assigned to workplaces (called from next workplace) according to a random rule. The probability that vehicles are assigned to machine i when they complete a delivery task at machine k, is a function of the proportion of those transportation requirements to be transported to and unloaded at machine k, calculated as

$$fd_k = \frac{\sum_{i=1}^{n} f_{ik}}{\sum_{i=1}^{n}\sum_{j=1}^{n} f_{ij}} \tag{6}$$

and the proportion of those transportation requirements to be picked up at machine i and transported to some other places, calculated as

$$fs_i = \frac{\sum_{i=1}^{n} f_{ik}}{\sum_{i=1}^{n}\sum_{j=1}^{n} f_{ij}} \quad (7)$$

So the probability that a vehicle request at machine i is satisfied by a vehicle at machine k is $fd_k \cdot fs_i$. The average empty vehicle travel distance per trip can be then calculated as

$$d_e = \sum_{i=1}^{n}\left[fs_i \sum_{k=1}^{n}\left(fd_k \cdot d_{ki}\right)\right] \quad (8)$$

The model, named here KOO-JANG model, calculates total empty travel as average travel distance per empty trip multiplied by number of empty trips (which is equal to the number of full trips), as

$$D_e = \left(\sum_{i=1}^{n}\left[fs_i \sum_{k=1}^{n}\left(fd_k \cdot d_{ki}\right)\right]\right)\cdot \sum_{i=1}^{n}\sum_{j=1}^{n} f_{ij} \quad (9)$$

Analysis of the models presented in mentioned papers, as well as plenty other papers dealing with AGV system design (for more info about AGV systems' design and control issues see review papers [5] or [6]), revealed that the performance of internal transport systems using AGVs depends on several factors such as number of trips between locations and distances (guide-path layout), but also vehicle scheduling and routing system. Exact information about load arrivals is usually only known a little moment in advance, therefore scheduling vehicles in these systems in advance is nearly impossible. The best solution is to use on-line dispatching rules [7]. It was proven that dispatching rules have unneglectable influence on AGV system's performances, so dispatching rules are a key factor in determining the amount of empty vehicle travel [8].Vehicle dispatching decisions are concerned with assigning vehicles and delivery requests to each other in real time based on the state of the system [9]. Some examples are rules such as random vehicle selection, longest idle vehicle selection, least utilized vehicle selection, nearest vehicle selection (as workplace initiated task assignment rules), or random workcenter, shortest travel time, maximum outgoing queue size, minimum remaining outgoing queue space, etc. (as vehicle initiated task assignment rules). However, in non-automated discrete material handling systems without computer control most dispatching rules are not possible to employ (or at least they are impractical to empower). In some applications of AGV systems there are only a few vehicles and jobs involved, with the simple scheduling algorithms. Jobs are usually handled in a First-come-First-serve (FCFS) fashion, and the nearest idle vehicle is usually chosen to serve a new job. The mission of routing is to find a suitable route (e.g. shortest-distance path, shortest-time path or minimal energy path) for every AGV from its origin to destination based on the current traffic situation. The route must be congestion-, conflict- and deadlock-free [10]. Here again, in non-automated discrete material handling systems with one or few human driving vehicles routes are chosen by driver and it could be assumed that there are no conflicts, congestions, while routes are simple to find optimal.

So in this paper above mentioned analytical models are applied to a classical production system where the vehicle is free to move in all directions between workplaces (along paths), and tasks are assigned to a free vehicles (random selection) according to the FCFS strategy.

3. SIMULATION ANALYSIS

For simulation analysis one simple production process was selected, consisting of 4 products processed in a production system with 8 discrete locations in a layout – inbound storage US (raw material warehouse), 6 workplaces RM 1 – RM 6 (machines) and outbound storage IS (finished goods storage). Simulation model was built in Enterprise Dynamics 10 simulation software. Figure 1 presents the 2D model layout representing layout of the production system, which was also used to calculate distance matrix needed for analytical models. Technological processes of products (sequences of visiting workplaces) are given in Table 1, used also to define from-to matrix (number of trips between locations).

Table 1. Routing of products (sequences of operations)

Product	Sequence of operations
P1	US – RM 1 – RM 3 – RM 5 – RM 2 – RM 4 – RM 6 - IS
P2	US – RM 5 – RM 3 – RM 1 – RM 6 – RM 4 – RM 2 - IS
P3	US – RM 3 – RM 4 – RM 5 – RM 1 - IS
P4	US – RM 2 – RM 6 – RM 4 – RM 3 - IS

Additional data, like processing time per unit load, were selected for the purpose of simulation in a way not influencing vehicle's travel. The average velocity of vehicles was set to 3 m/s (acceleration and deceleration neglected), while loading and unloading time per unit load was 5 seconds. Simulation runs were set to 50 hrs (assuming no shift breaks).

The simulation analysis was done with 4 different experiments [11]. In first experiment production volume (number of products processed in a given time - throughput) was varied, in one selected layout. The idea was to analyse possible influence of intensity of work (vehicle's utilisation) on empty travel and estimation error (deviation from simulation results). In second experiment three additional layout setups were made (changing locations of machines) for a selected throughput. The idea here was to analyse possible influence of layout design (variation of full travel for same production volume) on empty travel and estimation error. Third and fourth experiment were same as first two, however additional vehicle was used.

3.1 Experiment 1 – influence of production volume

In experiment 1 production volume was varied in 5 different scenarios (M1-M5), leading to the utilisation of the vehicle from 34% till 93%. Table 2 presents results obtained with simulation and 5 analytical estimation models. As could be seen, 3 models (that are assuming FCFS dispatching rule) estimates empty travel quite well, while MAXWELL-MUCKSTADT and BEISTEINER 2 models heavily underestimates empty travel. EGBELU and KOO-JUNG models were most accurate, however most simple BEINSTEINER 1 model is not much worse. The greater influence of traffic intensity (vehicle's utilisation) is noticed for low utilisation, were models tend to have slightly higher deviations (overestimation), however no correlation was found.

3.2 Experiment 2 – influence of layout design

In experiment 2 three new layouts were made, each defining different distance matrix. Simulation and analytical estimation of empty travel, presented in Table 3 (different layouts are marked L1-L4), were obtained for two selected production volumes, one with lowest vehicle's utilisation (M1) and one with highest vehicle's utilisation (M5). Again, as expected, same 3 models as in previous experiment proved useful. However some findings were interesting. According to the simulation results in un-optimized layouts, increased full travel (in table shown as full travel time, FTT in percentage of total time) is not followed by the same amount of increased empty travel. So analytical models, where calculation of empty travel is based on full travel, tend to estimate higher amounts of empty travel. However errors are still within several percent, expect BEINSTEINER 1 model where deviations in overestimating empty travel are up to 25%.

3.3 Experiments 3 and 4 – 2 vehicles

Experiments 3 and 4 were extensions of previous two, with added vehicle and corresponding increase of production volume. In experiment 3 production volume was varied in 10 different scenarios (added cases M6-M10). In experiment 4 same four layouts as before were used for two selected production volumes (again representing low and high vehicle's utilisation). Due to the need of increased product volume for analysis of high utilisation of two vehicles, simulation model had to be slightly reworked by adding additional machines per locations. However this wasn't affect distance matrixes because workplaces were in this case workcentres (same location of pick-up and delivery for all machines in a workcenter). The results are presented in Table 4 and Table 5. The findings are as follows. Increase of production volume increases full travel and empty travel. However analytical models are estimating higher amounts of empty travel compared to the simulation results. The differences in models were also noticed. While BEINSTEINER 1 model always overestimates empty travel (up to 13% in case of extremely low utilisation), EGBELU and KOO-JUNG models were more precise, slightly overestimating empty travel in cases of low utilisation while slightly underestimating empty travel in cases of high utilisation of vehicles. Changes in layout confirmed findings from experiment 2. Increased full travel in un-optimized layouts is leading to estimation of higher amount of empty travel in analytical models. BEINSTEINER 1 model again tends to have significant deviations in some cases.

4. CONCLUSION

Presented analysis of five analytical models for estimation of empty travel of discrete vehicles showed that using estimation models without knowledge of assumptions (in this case dispatching rules and control of the system) could lead to heavily underestimated results if one decides to use BEISTEINER 2 or MAXWELL-MUCKSTADT model. Other presented models quite well estimate empty travel, while EGBELU and KOO-JANG models being more accurate than BEISTEINER 1 model. The errors (deviations from the simulation results) of three analytical models are usually within several percent (except BEISTEINER 1 model in some exceptional situations).

Also, a certain influence of production volume and layout design on estimated empty travel time deviations has been established. Increasing full travel of vehicles analytical models tend to estimate higher amounts of empty travel than was obtained by simulation. However this should be taken with a caution, because only one layout with four variations was analysed.

Since total transport time which leads to the required number of vehicles is composed of full travel time, empty travel time, loading time and unloading time, small errors of empty travel time are causing even smaller overestimation or underestimation of total transport time required. At least in early stages of internal transport system design estimation models could be used. But again, models can't take into account different dispatching rules and possible blockings and congestions in case of larger fleets. So in this cases, and especially for final verification of chosen transport system, simulation is preferred.

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Figure 1. Layout of the simulation model

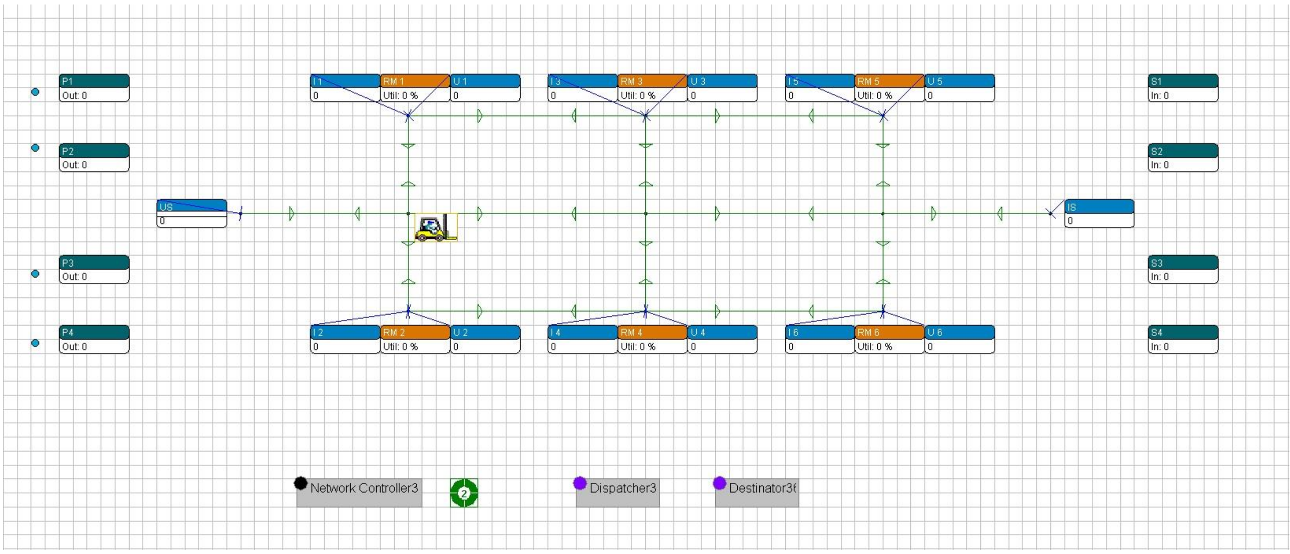

Table 2. Empty travel time (t_e) and deviations of analytical models from experiment 1

Scenario	Nr of products	Sim.	Beinsteiner 1		Beinsteiner 2		Egbelu/Koo-Jang		Maxwell-Muckstadt	
		t_e, s	t_e, s	Dev., %	t_e, s	Dev., %	t_e, s	Dev., %	t_e, s	Dev., %
M1	381	18666	20365	9,10%	3484	-81,34%	19602	5,01%	7366	-60,54%
M2	549	29016	30012	3,43%	5078	-82,50%	28556	-1,59%	10614	-63,42%
M3	716	38304	38965	1,73%	6267	-83,64%	37052	-3,27%	13843	-63,86%
M4	884	46692	48229	3,29%	8212	-82,41%	45698	-2,13%	17091	-63,40%
M5	994	53334	54987	3,10%	9168	-82,81%	52444	-1,67%	19217	-63,97%

Table 3. Empty travel time (t_e) and deviations of analytical models from experiment 2

Scenario	Simulation		Beinsteiner 1		Beinsteiner 2		Egbelu/Koo-Jang		Maxwell-Muckstadt	
	FTT, %	t_e, s	t_e, s	Dev., %	t_e, s	Dev., %	t_e, s	Dev., %	t_e, s	Dev., %
M1 - L3	10,89	18882	19594	3,77	3352	-82,25	19600	3,80	7366	-60,99
M1 - L1	11,33	18666	20365	9,10	3484	-81,34	19602	5,01	7366	-60,54
M1 - L4	13,14	18900	23588	24,80	4035	-78,65	20209	6,93	7366	-61,03
M1 - L2	13,85	19278	24921	29,27	4263	-77,89	20333	5,47	7366	-61,79
M5 - L3	29,18	53766	52335	-2,66%	8725	-83,77%	52444	-2,46%	19217	-64,26%
M5 - L1	30,66	53334	54987	3,10%	9168	-82,81%	52444	-1,67%	19217	-63,97%
M5 - L4	35,78	51426	64245	24,93%	10711	-79,17%	53855	4,72%	19217	-62,63%
M5 - L2	36,92	53244	66087	24,12%	11016	-79,31%	53825	1,09%	19121	-64,09%

Table 4. Empty travel time (t_e) and deviations of analytical models from experiment 3

Scenario	Nr of products	Sim.	Beinsteiner 1		Beinsteiner 2		Egbelu/Koo-Jang		Maxwell-Muckstadt	
		t_e, s	t_e, s	Dev., %	t_e, s	Dev., %	t_e, s	Dev., %	t_e, s	Dev., %
M1	381	18018	20365	13,03%	3484	-80,66%	19602	8,79%	7366	-59,12%
M2	550	27936	30052	7,57%	5086	-81,79%	28560	2,23%	10633	-61,94%
M3	716	37278	38965	4,53%	6627	-82,22%	37052	-0,61%	13843	-62,87%
M4	884	46764	48229	3,13%	8212	-82,44%	45698	-2,28%	17091	-63,45%
M5	996	53046	55112	3,89%	9185	-82,68%	52567	-0,90%	19256	-63,70%
M6	1150	60714	62809	3,45%	10641	-82,47%	59736	-1,61%	22233	-63,38%
M7	1309	69678	72031	3,38%	12165	-82,54%	68204	-2,12%	25307	-63,68%
M8	1506	81108	83517	2,97%	14069	-82,65%	78660	-3,02%	29116	-64,10%
M9	1796	96768	98519	1,81%	16727	-82,71%	93097	-3,79%	34723	-64,12%
M10	1989	109692	110025	0,30%	18342	-83,28%	104949	-4,32%	38454	-64,94%

Table 5. Empty travel time (t_e) and deviations of analytical models from experiment 4

Scenario	Simulation		Beinsteiner 1		Beinsteiner 2		Egbelu/Koo-Jang		Maxwell-Muckstadt	
	FTT, %	t_e, s	t_e, s	Dev., %	t_e, s	Dev., %	t_e, s	Dev., %	t_e, s	Dev., %
M1 - L3	10,89	17910	19594	9,40%	3352	-81,28%	19600	9,44%	7366	-58,87%
M1 - L1	11,31	18018	20365	13,03%	3484	-80,66%	19602	8,79%	7366	-59,12%
M1 - L4	13,11	18306	23588	28,85%	4035	-77,96%	20209	10,40%	7366	-59,76%
M1 - L2	13,87	18090	24921	37,76%	4263	-76,43%	20333	12,40%	7366	-59,28%
M10 - L3	58,35	104616	104746	0,12%	17459	-83,31%	104967	0,34%	38454	-63,24%
M10 - L1	61,32	109692	110025	0,30%	18342	-83,28%	104949	-4,32%	38454	-64,94%
M10 - L4	71,63	108378	128476	18,54%	21414	-80,24%	107677	-0,65%	38415	-64,55%
M10 - L2	73,95	105930	132604	25,18%	22104	-79,13%	107977	1,93%	38357	-63,79%

